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# Study of thermochromic glass performance in the Danish climate and visual comfort perspectives

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**Abstract**. Windows are key elements in the building envelope in terms of energy performance and comfort. The recent development of a new generation of so-called smart thermochromic glazings with the purpose of improving thermal comfort inside buildings raises the question of the visual comfort level offered by such glazings. This paper looks into the response of several commercial products to the specific Danish climate by running numerical simulations of a single-room building with the *Energy Plus* (*DesignBuilder)* software. The study case has a central window on each wall. The study highlights that the thermochromic effect is not activated for a major part of the year. In addition, we point out the decisive influence of the sky condition, as well as the non-negligible wind influence on the thermochromic response. Regarding indoor illuminance comfort, we observe a very variable annual performance depending on the tested thermochromic glazings. Moreover, we notice that thermochromism causes an increase in under-lighted annual time, which raises comfort issues, especially in a Nordic context.

## 1. Introduction

The building sector accounts for about one-third of global energy consumption and is responsible for a third of $CO_2$ emissions in both developed and developing countries [1]. At the same time, the modern lifestyle makes people spend 90% of their time indoors. It thus raises issues of indoor comfort such as natural light management [2].

Windows are the interface between the inside and the outside, through which light and heat flow. Identified as the weakest thermal element in the building envelope [3], windows have been a priority target to develop new innovative solutions in order to improve building performance and respond to stricter regulations. To take up the challenge, a new generation of smart thermochromic (TC) glass has been recently developed.

TC glass is a material which transmittance changes with its temperature. An autonomous adaptation of glass transmittance is an interesting asset for comfort performance of buildings. By adapting its tint with temperature, the TC glass regulates heat gains and reduces indoor overheating issues. To this day, Vanadium dioxide ($VO_2$) is one of the most promising thermochromic component implemented in polymeric films for windows [4] [5]. It presents a transition temperature Tc around which the thermochromism is active or not, with corresponding transmittance properties. With a view on practical implementation, it is possible to dope the Vanadium dioxide with complementary elements in order to lower its transition temperature.

Approaches such as in [6] and [7] investigate the effect of different doping components and the influence of their mode of implementation. In this way, [6]'s work looks into the transmission properties of a $VO_2$-based film with the addition of $ZnCl_2$, while [7] studies the effects of a co-doping procedure with fluorine and tungsten. Other approaches focus more on the structural properties of thermochromic systems, like [8] that studies the coexistence of phases in the material depending on its temperature, or [9] that points out the link between the crystallization level of a thermochromic structure and its transition temperature.

With a view on practical implementation on real-scale models, the reduction of cooling energy consumption is also studied with interest. [10] studies the potential heating and cooling energy savings associated with TC glazings implementation. It has been shown that such material could significantly reduce cooling loads in a building: around 30% energy savings compared to other glazing systems. In [11], a $VO_2$ double window system uses 11.1% less cooling energy than a classic double window. Moreover, [12] shows that TC glazings implemented in ventilated façades can reduce heating loads from 15% to 30% during winter in Russian climatic conditions, and can reduce cooling loads of about 30-40% during the summer season, thus avoiding the use of air conditioning.

It must be noticed that thermochromism remains, in all cases, a passive system with no possibility of being manually controlled by the user. For this reason, electrochromic glazings have been identified as commercially more attractive and have benefited from more research until now.

First designed to limit overheating issues by stopping infrared radiations, TC glazings also influence indoor illuminance and light characteristics by affecting the transmitted visible radiations. In the built environment, light is considered an important vector of well-being for humans since it biologically affects them in several ways: visual (retinal ocular system sensitive to "visible light"), direct skin absorbance, and non-visual ocular action (other physiological and neuronal pathways). Consequently, a large variety of parameters such as light quality and quantity, rhythm and periodicity of light events are involved in visual comfort considerations. Moreover, humans are fundamentally and biologically connected to light and daylight through their circadian clock. The influence of daylight on the latter depends on the duration of exposure, the light spectrum, its intensity, and its spatial disposition. Daylight especially holds the role of biological metronome for the day/night cycle. Therefore, as a dynamic and adaptive process, thermochromism brings the question of visual comfort for occupants.

This paper investigates the visual comfort performance of TC glazings in Nordic buildings under Danish climate conditions.

## 2. Numerical approach and modelling methods

This work investigates the response of the following five commercial thermochromic glazing systems evaluated from the indoor illuminance point of view:

- Thermochromic Suntuitive® (Pleotint company)
- 3 separate thermochromic glazing systems of Lawrence Berkeley National Laboratory (LBNL)
- Thermochromic Ravenbrick® (RavenWindow company)

The objective of this paper is to evaluate the influence of the thermochromic response on the visible light availability for the building occupants and to observe if visual comfort conditions are still respected with the implementation of such glazings in a Danish climate. Table 1 summarizes the visible light transmission properties ($\boldsymbol{T_{vis}}$) of the studied glazing systems and illustrates their expected wide performance range:

- Wide and sharp transition area (Suntuitive® and Ravenbrick®)
- High visual transmittance property in the clear state (Suntuitive® and LBNL 1)
- Moderate visual transmittance property in the clear state (LBNL 2)
- Low visual transmittance property in the clear state (Ravenbrick® and LBNL 3)

**Table 1.** Thermochromic glazings studied, with $\boldsymbol{T_{int}}$ the transition temperature area.

| Glazing system | Producer | $T_{int}$ transition state | $T_{vis}$ in clear state |
|---|---|---|---|
| **Thermochromic Suntuitive®** | Pleotint | 5 °C to 95 °C | $T_{vis} > 0.6$ |
| **Lawrence Berkeley National Laboratory 1** | LBNL | 25 °C to 75 °C | $T_{vis} > 0.6$ |
| **Lawrence Berkeley National Laboratory 2** | LBNL | 25 °C to 75 °C | $T_{vis} \sim 0.55$ |
| **Lawrence Berkeley National Laboratory 3** | LBNL | 25 °C to 75 °C | $T_{vis} < 0.36$ |
| **Thermochromic Ravenbrick®** | RavenWindow | 34 °C to 35 °C | $T_{vis} < 0.36$ |

This study is carried out with numerical simulations on EnergyPlus software (version 2.13) using DesignBuilder interface (version 5.2.0.145). TC glasses are defined as group pane components, whose adaptive behaviour is defined by a finite number of states corresponding to given surface temperatures. Thermochromic insulated glazing units (IGU) are modelled as presented in Figure 1. The model is a single-room building following the geometry defined in Figure 2, Table 2 and Table 3. Each of the four walls (East, West, North, South) in the study case model comprises a window. The outdoor weather file used for the simulations comes from IWEC data, ASHRAE project, and represents a typical Danish climate in Copenhagen (*weather file Copenhagen 061800*).

**Table 2.** Opening dimensions.

| | |
|---|---|
| Width | 1.2 m |
| Height | 1.2 m |
| Windows height | 0.9 m |

**Table 3.** Model external dimensions.

| | |
|---|---|
| Width | 5.0 m |
| Height | 2.8 m |
| Depth | 5.0 m |
| Internal floor surface | 25 m² |
| Internal volume | 70 m³ |

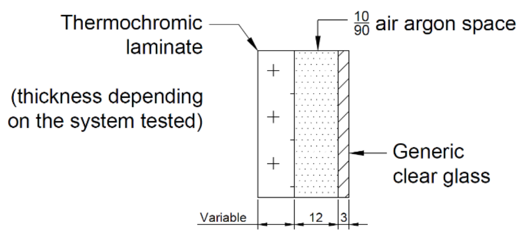


**Figure 1.** Single-room building model, DesignBuilder.

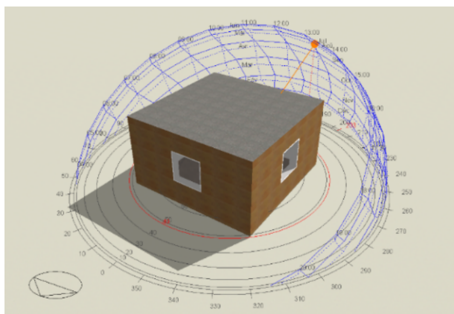

**Figure 2.** Thermochromic IGU definition, from WINDOW 7.6 software.

The characterization of the thermochromism visual comfort performance relies on parameters such as the active time of thermochromism, considered as the time during which glass darkens with temperature, independently of its darkening level. The visual comfort zone was set from the illuminance point of view. Over-lit and under-lit annual times were considered with respective illuminance thresholds of 750 lux and 250 lux.

Based on these parameters, specific simulation approaches look into the influence of the wind and the sky condition on the thermochromic response of the studied models. The wind exposure ranges from low (site protected) to high (site exposed). The choice of wind exposure also influences the heat transfer through the building envelope. DesignBuilder is supplied with a database of wind pressure coefficients based on data from [13].

## 3. Results and discussion

### *3.1. Thermochromism under standard Danish climate conditions*

Simulation results highlighted the close relationship between thermochromic behaviour of glazings and the nature of solar radiations to which they are exposed, which directly affects the indoor illuminance level. As a common trend to all glazings, the thermochromism remains inactive or relatively inefficient a major part of the year. This is mainly because of the cold Nordic climate conditions during autumn and winter (see Figure 3). However, the triggering of the thermochromic effect has been observed in warm periods (mostly spring and summer), implying an improvement of the occupants' visual comfort by reducing the over-lit annual time ($E > E_{sup} = 750\ lux$) (see Figure 3). A simultaneous increase in the under-lit annual time ($E < E_{inf} = 250\ lux$) can be noticed, causing more important needs for artificial lighting.

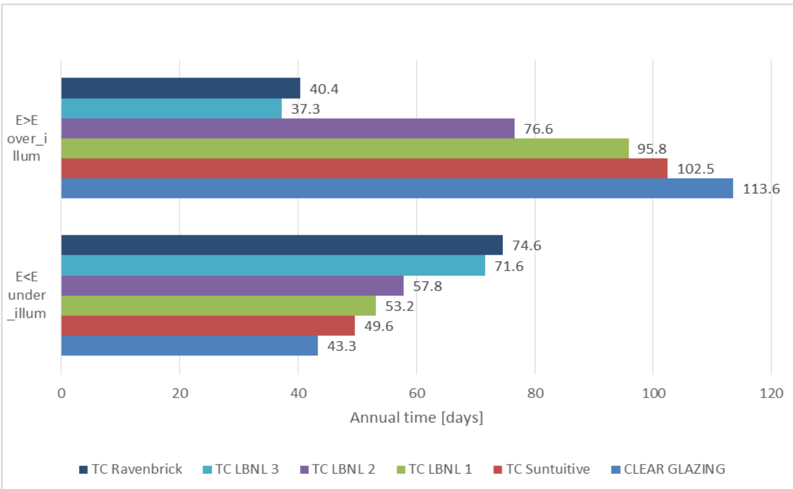


**Figure 3.** Annual time of indoor over / under-illuminance for standard Nordic climate conditions.

The detailed hour-by-hour analysis presented in Figure 4 for the Suntuitive® glazing on the 4th of May under a clear sky, highlighted a reduction in indoor illuminance from 30% to 55% during the day compared to clear glazing. The thermochromic effect – triggered from 12:00 to 17:00 – has a contribution of 10% to 35% in this reduction, in addition to the initial permanent tint of the Suntuitive®

glass. One can notice that the illuminance peaks (at about 7:12 and 17:00) are due to direct sunlight reaching the sensor of the model, whereas the walls cover it during the day as the sun's position changes.

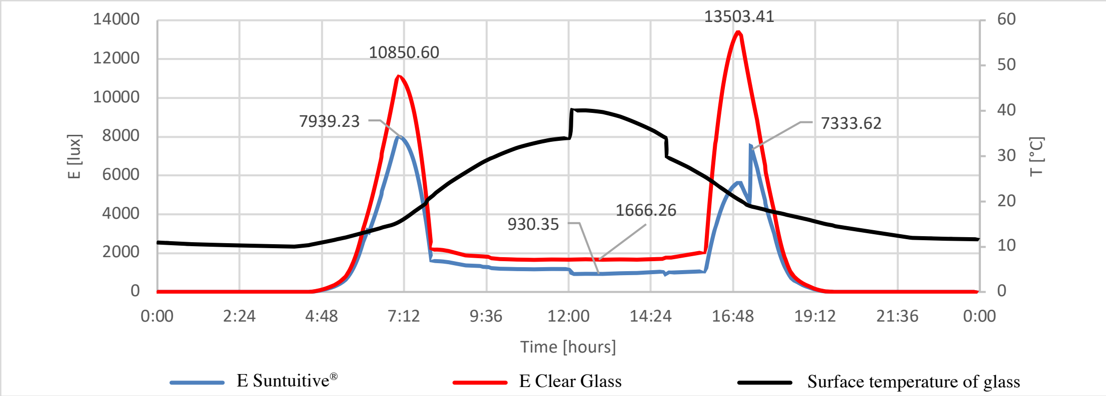


**Figure 4.** Indoor illuminance (E) level and surface temperatures during the 4th of May: difference between the Suntuitive® glazing and a generic clear glazing.

### 3.2. *Influence of wind exposure*

The successive simulations of sheltered and exposed building sites made it possible to look into the influence of wind exposure on thermochromic response of glazings. Wind and long-wave radiation exchange with the sky can have a cooling effect on glazed surfaces and thereby can lower the thermal exchange coefficient of external surfaces. By implementing a common scale based on visible transmittance $T_{vis}$, results show that high wind exposure causes a reduction of active thermochromism time from 4.6% to 8.3% depending on the glazing. In average, the mean active time represents 60% of the annual daytime for Suntuitive® glass, around 20% for LBNL models, and 7% for Ravenbrick® glass.

One should notice that the modelling of the outdoor convective heat transfer in the simulations is important for understanding the above conclusions. Radiation and convection are divided and vary independently. The convection algorithm is a dynamic adaptive program that considers a total of four different categories for surfaces and depends on current wind direction and heat flow directions. On the other hand, the model used for solar radiation calculation is the *ASHRAE clear sky solar model*, updated since 2009 to *ASHRAE revised clear sky solar model* ("tau" model) [14].

### 3.3. *Sky condition*

The influence of sky condition on thermochromism was studied for different seasons, under both clear and overcast sky conditions. In this study, the selection of days for different seasons, including both autumn and spring, is particularly important due to a number of interesting variations in the combination of solar radiation intensity and thermal conditions.

Sky clearness was simulated according to the EnergyPlus scale: an overcast sky characterized by dominant diffuse solar radiations is ranked 1; a hypothetical perfectly clear sky is ranked 6. Results showed that the external surface temperature of glazings highly depends on the nature of solar radiations. No thermochromic response is observed under overcast sky, even during warm periods of the year. On the contrary, spring, summer and even autumn clear sky conditions trigger thermochromism by raising surface temperature to 30 °C or higher.

## 4. Conclusion

We performed a series of simulations to study the response of TC glazing models during typical Danish weather scenarios. In this Nordic context, we firstly noticed that these glazings show a static behaviour in "cold" state for a major part of the year. Beyond annual performance in standard conditions, we can also observe the significant influence of wind exposure, sky condition and cloud cover. This questions the implementation of such glazing in Denmark, unfavourable from this point of view for the performances of thermochromic glazing. However, we can also observe a real advantage in the use of such smart glass in spring and summer periods. Nonetheless, thermochromism brings new architectural possibilities by limiting the overheating issues during a sunny day, opening the way to larger glazed surfaces on the facades.

This numerical study is based on the simulation of illuminance levels, surface temperature of glasses and glare effects. Regarding the performance of current simulation tools, this first work must be completed and expanded by additional experimental work, especially regarding the visual comfort issues. To this day, only isolated factors have been developed to characterize visual comfort: Correlated Color Temperature (CCT), Color Rendering Index (CRI, or CIE Ra), etc. However, it can be questioned whether those indicators are sufficient to characterize the performance of thermochromic and other dynamic glazing systems.

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